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Co-production of synfuels and electricity from coal + biomass with zero net carbon emissions: an Illinois case study

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Abstract

Energy, carbon, and economic performance are estimated for facilities co-producing Fischer-Tropsch Liquid (FTL) fuels and electricity from a co-feed of biomass and coal in Illinois, with capture and storage of by-product CO_2. The estimates include detailed models of supply systems for corn stover or mixed prairie grasses and of feedstock conversion facilities. The Illinois results are extrapolated to estimate the potential FTL production in 23 states.
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Keywords: Fischer-Tropsch; biomass; corn stover; grasses; coal; Illinois; greenhouse gas emissions: economics; carbon capture and storage.

1. Introduction

In the U.S., there is intense interest in secure domestic alternatives to oil for satisfying transportation energy needs. Significant energy supplies for meeting these challenges are biomass and coal. Biomass used for liquid fuels in the U.S. has historically been corn converted to ethanol. However, concerns about food price impacts and indirect land use impacts of growing biomass for energy on croplands have led to a growing emphasis of biofuels production efforts on non-food, non-cropland feedstocks – such as crop and forest residues and energy crops that can be grown on degraded lands. Such feedstocks are nearly "carbon neutral" since CO_2 released to the atmosphere in using the biomass is recycled via photosynthesis. As oil prices have risen, coal-to-liquid (CTL) fuels, especially Fischer-Tropsch liquids (FTL) have gained attention. But using FTL fuels made from coal without capture and storage of by-product CO_2 results in net GHG emissions that are roughly double those from petroleum fuels [1]. Even with CO_2 capture and storage (CCS) at the plant, the net GHG emission rate would only be approximately the same as for the crude oil products displaced.

One approach to producing coal-based liquid fuels with lower net lifecycle GHG emissions than petroleum-derived fuels is to co-process coal and biomass and capture and store the by-product CO_2 (CBTL-CCS, coal-

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biomass-to-liquids with CCS). The storage of photosynthetically-derived CO_2 provides negative GHG emissions to offset positive coal-related CO_2 emissions. Utilizing biomass in this fashion enables economies of scale inherent in coal conversion to be exploited for biomass, with average feedstock costs that are lower than for a facility processing only biomass. Since the CBTL-CCS idea was first introduced [2], the concept has attracted much government and industrial interest [3,4,5,6]. Utilizing the comprehensive analytical framework and database described by Kreutz, *et al* [1], we present a performance and cost analysis of CBTL-CCS systems located at an Illinois coal mine mouth site. We consider as biomass feedstocks corn stover or low-input, high-diversity perennial grasses grown on Conservation Reserve Program (CRP) lands or abandoned and degraded former cropland.

2. Feedstock supply costs

We assume coal is available at the U.S. Energy Information Administration's projected 2020 mine mouth reference price for the interior U.S. ($1.44/$GJ_{HHV}$) [9]. (All costs/prices in this paper are given in mid-year average 2007 dollars.) For comparison, the average mine mouth price in Illinois in 2007 was $33.6 per short ton [10], or $1.36/$GJ_{HHV}$ for our coal (Table 1).

Table 1. Feedstock characteristics.[a]

	Coal	Stover	MPG
Proximate Analysis (weight%, as-received)			
Fixed carbon	44.19	17.15	18.1
Volatile matter	34.99	58.04	61.6
Ash	9.7	4.81	5.3
Moisture	11.12	20.0	15.0
LHV (MJ/kg)	25.861	12.473	14.509
HHV (MJ/kg)	27.114	13.932	15.935
Ultimate Analysis (weight%, dry basis)			
Carbon	71.72	44.50	46.96
Hydrogen	5.06	5.56	5.72
Oxygen	7.75	43.31	40.18
Nitrogen	1.41	0.61	0.86
Chlorine	0.33	0	0
Sulfur	2.82	0.01	0.09
Ash	10.91	6.01	6.19
HHV (MJ/kg)	30.506	17.415	18.748

(a) Properties are from [7] for bituminous coal (Illinois #6) and [8] for corn stover. Mixed prairie grasses (MPG) are assumed to have switchgrass properties [8].

To estimate delivered costs for the biomass feedstocks (Table 1), we carried out detailed analyses of the operations involved in production and delivery, assuming that the conversion facility will use 10^6 t/yr (dry matter). Our analysis took into account cultivation and storage operations at the field, biomass transport to the facility, and pre-processing at the plant to size the feedstock for gasification. We use an engineering-economic approach based on machinery parameters, e.g., speed, width, and field efficiency. Our transportation costs assume biomass is collected from a circle around the plant, with a road tortuosity factor of 1.4 and planting densities as discussed below.

We model mixed prairie grasses (MPGs) as a high-diversity mix of 16 native prairie grasses grown with low inputs on carbon-depleted soils, as proposed by Tilman, *et al.* [11]. Lehman [12] has estimated potential MPG yields on cropland on a county-by-county basis for the U.S. using a yield model with annual rainfall and temperature as inputs. A set of state-average MPG yields for selected US states derived using this model was provided to us by Tilman [13]. Following Tilman's suggestion, we developed a regression correlation (r^2 = 0.78) between state-average MPG yield and state-average hay yield (published by USDA [14]). This enables us to estimate average MPG yield for any state with known average hay yield. The resulting MPG yield for Illinois is 5.38 dry tonne per hectare per year, which we assume for our case study site. (Collection and storage losses result in a delivered yield of 4.75 dt/ha/yr.) We also assume, based on [11], an average soil/root C accumulation rate for the first 30 years of 0.3 tC per dry tonne of harvested MPGs, or equivalently 0.6 tC/tC in the harvested MPGs. We assume MPGs would be planted primarily on Conservation Reserve Program (CRP) lands, of which there were 0.43 million ha in Illinois in 2007. This is 3% of Illinois' land area, which we take as the planting density around the conversion facility. Not all CRP land is suitable or desirable for planting with MPGs, but there are additional lands not used for cropland that might support MPGs: abandoned or degraded cropland (as defined in the Agricultural Census [15]). In Illinois, the land area thus categorized in 2002 was some 0.75 million hectares [16].

Delivered MPG costs and associated energy use and greenhouse gas (GHG) emissions are estimated assuming that in the establishment year seeds are purchased and the soil is ploughed and planted. The field is then harvested annually (after senescence) for thirty years (the assumed physical life of the conversion facility). Every year, MPGs are mowed and raked and then gathered in large rectangular bales containing 95% of the produced biomass. Bales are moved to the field edge, where they are tarped and stored, losing 7% of their dry matter in the process [17]. Bales are then hauled by trucks (42 bales per truck-load, which would contain about 15 dry tonnes) to the plant where they are ground before being fed to the gasifier. Providing 10^6 tonnes of MPGs to a plant with a 3% planting density involves an area larger than 6 million hectares, resulting in an average one-way hauling distance of 132 km. The energy requirements and greenhouse gas emissions associated with MPG production and delivery amount to 1 GJ and 77 $kgCO_{2eq}$ per dry tonne, respectively, with transportation the dominant component (Fig. 1). The average cost of delivered MPGs is $132/tonne (dry basis), or $7.06/$GJ_{HHV}$. Land rent and truck transportation costs together account for over 60% of this cost (Table 2).

Table 2. Average delivered costs of corn stover and MPGs estimated for Illinois (2007 $).

	MPG	Stover
	YIELD (dt/ha/yr)	
Gross yield	5.38	9.34
Delivered yield (a)	4.75	3.82
COST OF BIOMASS, 2007$ per delivered tonne (dry) (b)		
LAND RENT (c)	**53.69**	-
ESTABLISHMENT (d)	**8.65**	-
Seeds	7.64	-
Ploughing	0.48	-
Seeding	0.53	-
HARVEST/COLLECTION (e)	**21.24**	**32.91**
Swather	8.65	-
Shredder (mower)	-	3.57
Wheel rake (V formation)	2.93	3.63
Large rectangular baler	9.66	11.96
Fertilizer replacement (f)	-	13.75
IN-FIELD TRANSPORT & STORAGE (g)	**12.89**	**13.69**
Stinger Stacker	9.12	9.69
Tarping	3.77	4.00
TRANSPORTATION (h)	**29.19**	**8.90**
Truck loading	1.66	1.76
Truck hauling	26.54	6.08
Truck unloading	0.99	1.06
PREPARATION FOR GASIFICATION (i)	**6.73**	**7.15**
Telescopic handler to feed the grinder	1.66	1.76
Grinder (self powered)	5.07	5.39
TOTAL COST, 2007$/dry tonne delivered	**132.38**	**62.66**
TOTAL COST, 2007$/$GJ_{HHV}$ delivered	***7.06***	***3.60***

(a) Delivered yield is gross yield less collection and storage losses.
(b) General assumptions: Real discount rate of 7%, machinery fuel price of $1.06/liter; wage rate of $10.28/hr, the 2007 average for farm labor [23];machinery purchase price 90% of list price; 1.1 hours of machine time per hr of field time; 1.2 hours of labour per hr of field time; insurance, housing and taxes 2% of equipment purchase price plus salvage value; lubrication costs 15% of fuel costs; interest charged on machinery variable costs (e.g., fuel, lubrication, repairs, etc.).
(c) For MPGs, land rent is assumed to be the average CRP contract payment for 2007: $255/ha [24]. No land rent charged for corn stover.
(d) For MPGs, establishment costs consist of seeds ($247.1/ha for a mix of C4 perennial grasses and forbs plus $271.8/ha for a mix of 4 legumes [13]), chisel plowing ($99.55/hr and effective field capacity – EFC – of 3.44 ha/hr), and seed drilling ($91.33/hr and EFC of 2.75 ha/hr). No establishment costs charged for corn stover.
(e) Harvest of MPGs involves mowing, swathing, raking into windrows, field-drying to 20% moisture, and then square-baling (1.2x1.2x2.4 m^3, 454 kg/bale). Field losses are 5% of gross yield. The swather costs $66.45/hr and has EFC of 2.10 ha/hr; the rake costs $37.31/hr and has EFC of 3.50 ha/hr; the baler costs $96.90/hr and has EFC of 2.75 ha/hr. Corn stover harvesting is similar to MPG harvesting, but mowing occurs during harvest of the primary crop, and shredding replaces swathing at a cost of $52.76/hr and with EFC of 3.84 ha/hr. Baled biomass is 44% of gross stover produced, and bale storage losses are 7%.
(f) Fertilizer replacement assumed: 1.6 kg_{P2O5}, 12.2 kg_{K2O} and 8.1 kg_{NH3} per dry t stover removed [25], with costs of $622/$t_{P2O5}$, $697/$t_{K2O}$ and $523/$t_{NH3}$ [26], and applied with regular fertilizer.
(g) A Stinger Stacker 4400 collects and piles bales at field edge at a cost of $137/hr and EFC of 32 bales/hr. At field edge, the bales are manually tarped with help of a JCB 520 telescopic handler costing $46/hr and having an EFC of 54 bales/hour.
(h) Bales are loaded and unloaded with a telescopic handler costing 46.43 $/hr and having EFC of 102 bales/hr when loading and 170 bales/hr when unloading. Transport is by 16-meter flatbed trailer truck carrying 42 bales. Trucks cost 75.70 $/hr with an EFC of 31 bales/hour. Transportation cost includes empty return of trucks. Average one-way transport distances are 132 km for MPGs and 28.5 km for corn stover.
(i) The grinder costs 86.62 $/hr and processes 26.29 t/hr. Bales are fed using a telescopic handler. See note (h).

For corn stover, we assume a gross weight yield equal to corn grain yield (dry basis) [18,19]. Applied to Illinois, this gives 9.34 dry t/ha/yr of stover (average 2007 yield), some of which must be left on the field for soil maintenance [20]. Some recent research [21] suggests that all stover should be left on the soil to sustain soil organic matter, but most prior work suggests some stover removal is acceptable, but with variations that depend on local soil and climate [22].

When removing stover, as much as 50-70% of the gross yield remains on the field due to machinery inefficiencies during collection and baling [27]. Our assumed machinery inefficiencies (based on [19]) and storage losses together result in 59% of the gross yield of stover being left on the field. We assume that this is a good proxy for the average amount of stover that must be left on the field for soil maintenance. Our estimates of stover removal are generally lower than estimates of acceptable removal by Graham, *et al.* [28], who took into consideration local soil moisture, water and wind erosion, crop rotation, and irrigation and tillage practices.

Delivered costs, associated energy use, and GHG emissions are estimated assuming the stover is shredded and raked, then packed in large rectangular bales that are moved to the field edge, where they are tarped for storage. Bales are trucked to a conversion facility, where the biomass is sized for feeding to a gasifier. Costs of establishment and land rent are attributed to the primary product (corn grain). However, a nutrient replacement cost is included for nutrients removed with the stover. Transportation costs are estimated assuming the stover density equals the density of land planted with corn in Illinois – 37% in 2007 [14]. Delivering 10^6 t/yr stover involves an area of 288,655 hectares, or an average one-way transport of 28.5 km. Associated energy use and GHG emissions are 1 GJ and 159 $kgCO_{2eq}$ per dry t, respectively, with fertilizer replacement accounting for the largest component (Fig. 1). The average delivered cost of stover is $63 per dry tonne ($3.6/GJ_{HHV}) (Table 2).

3. Plant design

Coal and biomass are gasified in separate trains before the resulting synthesis gas streams are mixed together for further processing. Synthesis gas that is not converted into FTL fuels in one pass through the synthesis reactor is used to generate substantial amounts of co-product electricity in a gas turbine combined cycle. This “once-through” (OT) process design provides for more attractive economics under a wide range of conditions compared to a design that recycles (RC) unconverted gas to increase FTL output [1,29]. One important feature of our plant design is the production of finished diesel and gasoline blendstocks. This is in contrast to most proposed FTL plants, which would produce middle distillates (a mix of jet fuel and heavy diesel) plus naphtha, which would be sold as a feedstock to the chemical process industry.

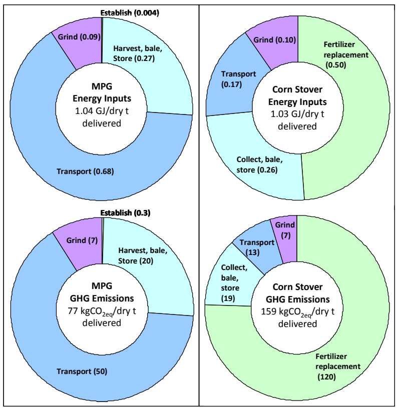

Figure 1. Energy use and GHG emissions for production + delivery of MPGs and stover.

Our CBTL plants have an input biomass capacity of 3,044 dry tonnes/day, and the coal input rate is set such that the CBTL-CCS designs produce FTL fuels with zero net lifecycle GHG emissions, considering all of the GHG flows indicated in Fig. 2. Exported electricity produces a GHG emissions credit, assuming it displaces electricity that would otherwise have been generated elsewhere on the grid. We choose to assign a GHG emission rate equal to the lifecycle emissions for a stand-alone coal IGCC plant with CCS (90% of CO_2 captured) because of the expectation that most new coal power plants to be built in the US will utilize CCS. (The emissions credit assigned to electricity is arbitrary and does not impact overall economics, which depends on total system GHG emission rate).

Table 3 shows our simulation results, alongside results for coal-to-liquids systems developed using the same analytical framework [1]. The fate of captured CO_2 is indicated by –V for venting and –CCS for capture and storage. Two of the coal-only systems utilize recycle of unconverted syngas (RC) to increase FTL production. The other two designs utilize once-through (OT) synthesis, as in the CBTL designs. The coal input rate is fixed for all of the coal-only designs at the rate required for the RC designs to produce 50,000 barrels per day of FTL fuels. The following observations follow from Table 3:

- Comparing coal-only RC-V and OT-V highlights the trade-off between FTL and electricity exports in these designs: FTL output falls by ¼ from the RC to the OT design, while net electricity exports are tripled. The additional electricity in the OT case is produced with efficiencies well in excess of those that can be achieved in standalone coal-IGCC systems [1,29]. Our CBTL-OT designs also feature these high marginal electricity generating efficiencies.
- Constrained by the biomass feedstock limitation of 10^6 t/yr and the objective of producing FTL with zero net GHG emissions (in the –CCS cases), coal use for the CBTL systems is much less than for the coal-only systems.
- Without CCS, GHG emissions for coal-only FTL production are at least double those for the crude oil products displaced (COPD). The CBTL system without CCS also has high GHG emissions, though not as high as the coal-only systems. With CCS, coal-only systems have emissions close to those of the COPD. For the CBTL-CCS designs, net GHG emissions associated with FTL fuels are zero (by design).
- For the CBTL design using corn stover biomass, net electricity exports fall modestly (14%) when CO_2 is captured rather than vented. This is a general feature of synfuels production: since a stream of nearly-pure CO_2 is intrinsically produced when making FTL fuels, the largest single energy penalty in adding CCS is compression of the captured CO_2 to enable pipeline transport and injection underground [1].
- The CBTL-OT-CCS design using MPGs produces considerably more FTL and power than the design using corn stover, because the added carbon storage in soil and roots with MPGs allows more coal input to the system while still producing net zero fuel cycle FTL GHG emissions.
- The effectiveness of CBTL systems in using biomass to make low-carbon liquid fuels is evident in the “FTL yield” (under Energy Ratios in Table 3), expressed in liters of gasoline equivalent per dry tonne of biomass input: 430 for the corn stover CBTL system and 740 for the MPG CBTL system. To put these numbers in perspective, Aden *et al.* [30] project that by 2010 cellulosic ethanol technology (without CCS) will be advanced sufficiently to enable an ethanol yield from corn stover of 269 liters of gasoline equivalent per dry tonne.

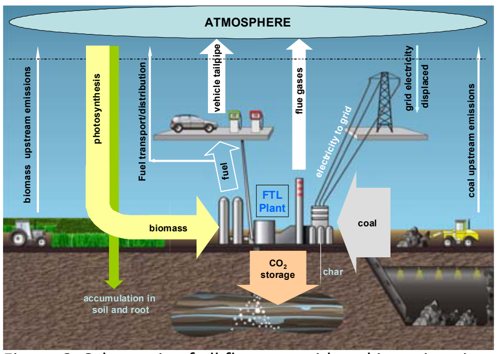

Figure 2. Schematic of all flows considered in estimating net fuel cycle greenhouse gas emissions.

4. Economics

We examine overall economics for a generic Illinois mine mouth plant site. Several possible locations can be identified in Fig. 3. Given that the potential availability of MPGs and corn stover are relatively high in Illinois (~2 million and ~20 million t/yr delivered, respectively) and relatively uniformly dispersed, access to mine mouth coal and to CO_2 injection sites may largely determine plant location. Coal underlies about 65% of Illinois' land area, and recoverable reserves account for nearly 10% of the U.S. total, but there are only a relatively small number of producing mines. Opportunities for CO_2 storage in the Illinois Basin have been investigated in detail by the Midwest Geological Sequestration Consortium [31], which identified the large Mt. Simon Sandstone formation as a good candidate. For specificity in estimating costs, we assume the CO_2 injection point to be 100 km from the plant site.

Table 4 shows installed plant costs (estimated using the framework and sources in [1]) for the CBTL and coal-only plant designs described in Table 3. Significant scale economies are apparent, with the large coal-only facilities having considerably lower specific costs than the CBTL facilities. The coal+stover CBTL systems, being the smallest among the plants considered, have the highest specific costs. However, the difference in cost between the same plant design with and without CCS is small – primarily the cost for CO_2 compressors, contributing to relatively low avoided GHG costs (Table 4, bottom row).

The levelized total costs of FTL fuels production are lower for coal-only systems than for CBTL systems when zero price is assigned to GHG emissions (Table 4), and designs that vent CO_2 have the lowest cost. In terms of breakeven oil price (BEOP) – the price of crude oil at which wholesale prices of crude oil products displaced (including a price for lifecycle GHG emissions) equals the FTL fuels cost (on a \$ per GJ_{LHV} basis) – coal-only systems have BEOPs of 35 to 53 \$/bbl. The CBTL systems only begin to compete at 72 \$/bbl.

Table 3. Performance simulation results. Coal-only results from Kreutz *et al.* [1].

Feedstock ➔	**Coal Only**				**Coal + Stover**		**Coal+MPG**
Process Configuration (a) ➔	**RC-V**	**RC-CCS**	**OT-V**	**OT-CCS**	**OT-V**	**OT-CCS**	**OT-CCS**
Coal input rate							
As-received, metric t/day	24,297	24,297	24,295	24,295	3,275	3,275	6689
Coal, MW LHV	7,272	7,272	7,272	7,272	980	980	2,002
Coal, MW HHV	7,625	7,625	7,624	7,624	1,028	1,028	2,099
Biomass input rate							
As-received metric t/day	-	-	-	-	3,805	3,805	3,581
Biomass, MW LHV	-	-	-	-	549	549	601
Biomass, MW HHV	-	-	-	-	614	614	661
% biomass HHV basis	-	-	-	-	37.4%	37.4%	23.9%
Total FTL production capacity (b)							
Diesel + gasoline, MW LHV	3,147	3,147	2,307	2,307	484	484	821
Diesel + gasoline, MW HHV	3,387	3,387	2,483	2,483	521	521	883
bbl/day crude oil products displaced	50,000	50,000	36,653	36,652	7,691	7,692	13,039
Electricity							
Gross production, MW	874	874	1,672	1,664	361	365	609
On-site consumption, MW	447	557	393	589	75	119	203
Net export to grid, MW	427	317	1,279	1,075	286	246	406
Energy Ratios							
FTL out (HHV)/Energy in (HHV basis)	44.4%	44.4%	32.6%	32.6%	31.7%	31.7%	32.0%
Net electricity/Energy in (HHV)	5.6%	4.2%	16.8%	14.1%	17.4%	15.0%	14.7%
FTL (HHV) + electricity/Energy in (HHV)	50.0%	48.6%	49.3%	46.7%	49.1%	46.7%	46.7%
Liters gasoline equiv / dry tonne biomass					434	434	736
C input as feedstock, kgC/second	**179**	**179**	**179**	**179**	**39**	**39**	**66**
C stored as CO_2	0	51.5%	0	51.1%	0	51.7%	50.9%
C in char (unburned)	5.0%	5.0%	5.0%	5.0%	6.9%	6.9%	6.2%
C vented to atmosphere	60.3%	8.9%	69.6%	18.6%	43.3%	17.5%	18.4%
C in FTL	33.7%	33.7%	24.7%	24.7%	23.3%	23.3%	23.9%
C stored, tCO_2 per hour	**-**	**1,217**	**-**	**1,207**	**-**	**272**	**442**
C stored, 10^6 tCO_2/yr (90% cap. factor)	**-**	**9.60**	**-**	**9.52**	**-**	**2.14**	**3.49**
Net Lifecycle GHG Emissions (c)							
kgCO2eq/GJ FTL LHV	200	94	259	118	153	1	-9
Relative to crude oil products displaced	2.18	1.03	2.83	1.28	1.67	0.01	-0.10

(a) RC = recycle synthesis; OT = once-through synthesis; V = vent CO_2; CCS = CO_2 capture and storage.
(b) Ratio of diesel to gasoline: 61/39 (energy basis), 57/43 (volume basis). Volumetric rates of FTL fuels are reported here as the volumetric rate of crude oil products displaced containing the same amount of energy (LHV basis).
(c) Electricity co-product GHG credit equal to lifecycle emissions from stand-alone coal-IGCC with 90% CO_2 capture (138 $kgCO_2$ equivalent/MWh, which includes 1.2 kgC_{eq}/GJ_{LHV} coal accounting for coal mining and transportation emissions).

Interestingly, despite the much higher cost of MPGs compared with corn stover, the FTL production cost is nearly the same for a CBTL system using MPG or stover due to *i)* the larger scale of the MPG CBTL plant and *ii)* the lower fraction of biomass input needed to achieve zero-GHG FTL fuels. The costs of avoided GHG emissions for all plants analyzed – $11 to $20 per tCO_{2equiv} – are considerably lower than avoided costs for stand-alone power generation, since energy and capital penalties of adding CCS are relatively small for synfuels production [1].

When GHG emissions are priced above $20/$tCO_{2equiv}$, FTL fuels from the coal-only OT-CCS system are the least costly option until the emissions price reaches $58/$tCO_{2equiv}$ (Fig. 4), despite the high GHG emissions associated with this coal-only design (Table 3). The corresponding breakeven oil price is about $38/bbl. A GHG emission price of $37/$tCO_{2equiv}$ is sufficient to make the CBTL options competitive with the RC-CCS coal-only design, with a corresponding breakeven oil price of about $56/bbl.

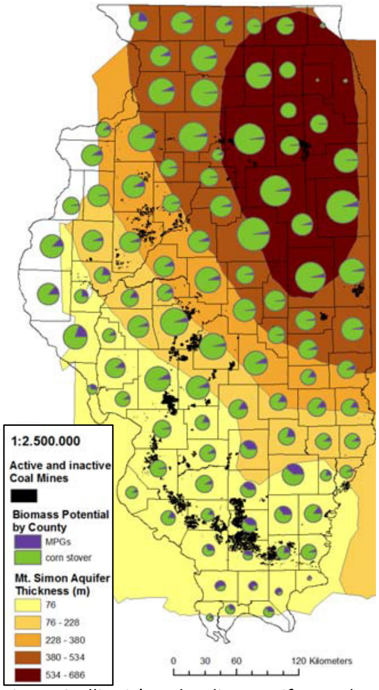

Figure 3. Illinois' coal, saline aquifer, and potential biomass resources. Total state biomass potential is apportioned by county according to fraction of corn production and CRP acreage in each.

5. Potential

We apply the same approach as for Illinois to estimate corn stover and MPG availability and cost in a swath of 23 central U.S. states that in 2007 accounted for 94% of U.S. corn production and ~12 million ha of CRP enrolments (86% of U.S. total).† We use 2007 corn yields and consider MPGs grown on acreage equivalent to CRP acreage in 2007.

The estimated total potential delivered MPGs in these states is 47 million t/yr grown from 2.7% of the land area of the states, with an average gross yield of 4.4 dry t/ha/yr, an average transport distance of 144 km, an average land rent of $123/ha/yr, and delivered at an average cost of $6.3/$GJ_{LHV}$ ($119/dry tonne). Delivered costs vary from a low of $5/GJ in Colorado due to low land rents and relatively higher density of CRP lands (3.7%) to a high exceeding $12/GJ in Tennessee due to higher land rents and lower density of CRP lands. Texas, Iowa, Colorado, Kansas, Montana, and N. Dakota together account for over half the potential MPGs.

The estimated potential for delivered corn stover in the 23 states is 131 million t/yr from 35 million ha (8% of the total area) producing an average of 4.2 t/yr stover (dry). The average transport distance is 52 km and the average delivered cost is $4/$GJ_{LHV}$ ($70/dry tonne). This weighted-average cost is determined largely by the five states (Illinois, Indiana, Iowa, Minnesota, and Nebraska) that account for 64% of the stover.

Table 4. Installed capital costs and levelized FTL production costs with zero GHG emissions price.

	Coal Only				Coal + Stover		Coal+MPG
	RC-V	RC-CCS	OT-V	OT-CCS	OT-V	OT-CCS	OT-CCS
Total plant cost (TPC), 10^6 2007$	4,878	4,945	4,407	4,597	1,245	1,281	1,944
Specific TPC, 2007$ per bbl/day	97,568	98,908	120,239	125,434	161,870	166,577	149,092
Levelized FTL cost, $/$GJ_{LHV}$							
Capital charges	8.42	8.53	10.37	10.82	13.96	14.37	12.86
O&M charges	2.18	2.21	2.69	2.81	3.62	3.73	3.34
Coal (@ $1.44/$GJ_{HHV}$)	3.49	3.49	4.76	4.76	3.06	3.06	3.68
Biomass	0.00	0.00	0.00	0.00	4.56	4.56	5.68
GHG emissions charge	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO_2 disposal charges	0.00	0.49	0.00	0.67	0.00	1.18	0.97
Electricity sales (@$60/MWh)	-2.26	-1.68	-9.24	-7.76	-9.84	-8.46	-8.24
Total, $/$GJ_{LHV}$	11.83	13.05	8.58	11.30	15.37	18.44	18.30
Total, $/gallon gasoline equiv	1.4	1.6	1.0	1.4	1.8	2.2	2.2
Breakeven oil price, $/bbl	53	59	35	50	72	89	88
Avoided GHG cost, $/$tCO_2$ equiv	-	11	-	19	-	20	no estimate

† Alabama, Arkansas, Colorado, Georgia, Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, Mississippi, Missouri, Montana, Nebraska, N. Dakota, Ohio, Oklahoma, S. Dakota, Tennessee, Texas, Wisconsin, Wyoming.

The potential MPG and corn stover resources in the 23 states, when used in CBTL systems described above, could produce 1.4 million barrels per day of zero-GHG emission FTL fuels (equivalent to ~10% of U.S. oil imports in 2007) and 400 TWh of decarbonized electricity (~20% of all U.S. coal fired power generation in 2007).

The biomass potential for coprocessing at CBTL plants is likely greater than these calculations suggest—even in these 23 states. These states contain a USDA-estimated 135 million hectares (~70% of U.S. total) of abandoned or degraded agricultural land that might be considered for growing MPGs. Other prospectively important biomass supplies include other crop residues and woody biomass supplies such as urban wood wastes and forestry residues: mill residues, logging residues, diseased tree kills, fuel treatment thinnings, and productivity enhancement thinnings.

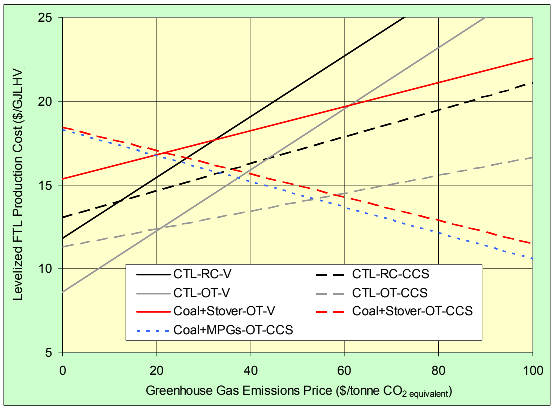

Figure 4. FTL production costs with GHG emission price. (Electricity sale price is $60/MWh + GHG charge at 2007 U.S. grid-average GHG emissions rate (636 kg CO2/MWh).

6. Conclusions

The plentiful biomass and coal resources of Illinois and good access to CO_2 storage sites makes it a good candidate for siting of facilities to co-produce low GHG emission liquid fuels and electricity. Under an aggressive CO_2 emissions mitigation policy, the economics of such CBTL-OT-CCS facilities appear attractive. The biomass resources in a wider (23-state) region in the central U.S. could support the production of a nationally-significant amount of zero-GHG transportation fuel and decarbonized co-product electricity.

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